Final Progress Report (March 2010-Feb 2011)
DARPA Contract No. W911NF-10-1-0049
Lehigh Fund No. 542212

Compact Modeling of MEMS Resonators

Subrata Halder and Jim Hwang

jh00@lehigh.edu

Summary

- Modeled and characterized MEM resonators fabricated by Nanyang Technological University in Singapore using novel low-temperature silicon wafer bonding
- Finite-element analysis performed by using ANSYS
- Compact model created in ADS design environment using Verilog-A portable code
- Resonance frequency matches that measured by laser Doppler vibrometer after adjusting cantilever thickness
- Effects of DC bias and AC drive simulated
- High leakage current broadens electrical resonance and prevents model validation

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	5 Apr 11	Final Progress Report (25 Feb 10 - 24 Feb 11)

4. TITLE AND SUBTITLE

Compact Modeling of MEMS Resonators

5. FUNDING NUMBERS

Grant W911NF-10-1-0049

6. AUTHOR(S)

Subrata Halder and James C. M. Hwang

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lehigh University, 5 E. Packer Ave., Bethlehem, PA 18015

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (Maximum 200 words)

The main accomplishment of this project was the development, for the first time, of a compact transient large-signal MEMS resonator model for large-scale integration of resonators and transistors. The four quarterly milestones, including electrical/mechanical/thermal characterization, preliminary resonator model, electrical/mechanical/thermal validation, and extended resonator model, were all. MEMS cantilever resonators were fabricated at Nanyang Technological University in Singapore by using a novel low-temperature wafer bonding process to realize 3D features that could not be realized in a single silicon wafer. The simple and relatively large design facilitated model development and validation. Using well-known characteristics of silicon, only the thickness of the cantilever was fine-tuned to match the modeled and measured resonance frequencies. A compact transient large-signal resonator model was developed and coded in Verilog-A, so that it could be readily installed in different circuit-design environments such as ADS and Cadence. The effects of DC-bias and AC-drive levels and frequencies were simulated in both time and frequency domains. The model validation was mostly through mechanical characterization by using a laser Doppler vibrometer. Electrical validation was more difficult due to high leakage current associated with the silicon substrate. Thermal validation was inaccurate due to weak temperature dependence.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Micro-electromechanical systems, radio frequency, resonator, compact modeling	17
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

Enclosure 1

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

(2) Student/Supported Personnel Metrics for this Reporting Period (25 Aug 10-24 Feb 11)
(a) Graduate Students
Ding, Guanghai, 100% supported, 8.33% FTE by this grant
Jin, Renfeng, 100% supported, 16.67% FTE by this grant
Ning, Yaqing, 100% supported, 16.67% FTE by this grant
Wang, Weike, 100% supported, 16.67% FTE by this grant
Total: 58.33% FTE by this grant

(3) Teehnology Transfer
Visited Army Rcscarch Laboratory in Adelphi, Maryland and gave seminar on 13 Sep 10
Followed the visit with review and comment via c-mail on test-strueture designed by ARL

(4) Scientific Progress and Aeeomplishments
Attached

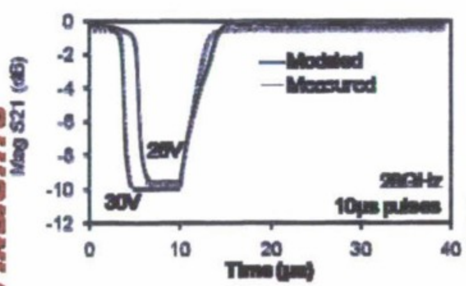
Compact Modeling of MEMS Resonators

Jim Hwang jh00@lehigh.edu

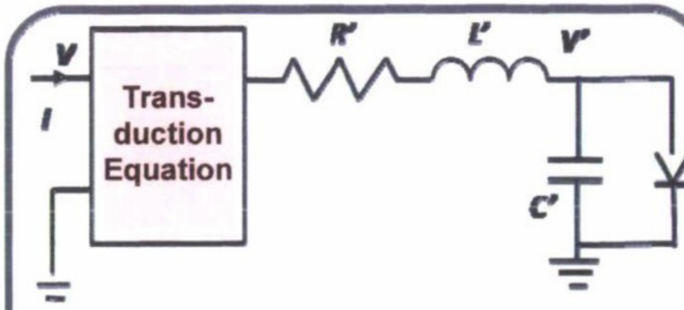
STATUS QUO

Existing MEMS device models are too complicated for popular circuit design environments or too simple to include transient (coupling) effects between devices.

NEW INSIGHTS



World's first compact model developed to smoothly bridge the pull-in, contact and release processes of electrostatically actuated RF MEMS capacitive switches.



TECHNICAL APPROACH:

- Equivalent-circuit model in SPICE-based design environment such as ADS & CADENCE
- Compact and robust with just the right amount of physics
- Hierarchical structure with different level of details for different accuracies
- Multi-physics including electro-mechanical, electro-thermal and thermal-mechanical effects
- Physical insights through detailed finite-element analysis and electrical and mechanical characterizations

ASSUMPTIONS AND LIMITATIONS:

- Tradeoff of compactness and accuracy
- Absence of automated mechanical load-pull microwave test setup

IMPACT

Design and simulation of integrated mechanical and electronic circuits for chip-scale spectrum and network analyzers, intelligent radios, jam-resistant communications terminals, sensors for analysis of vibration signatures and monitoring of structures.

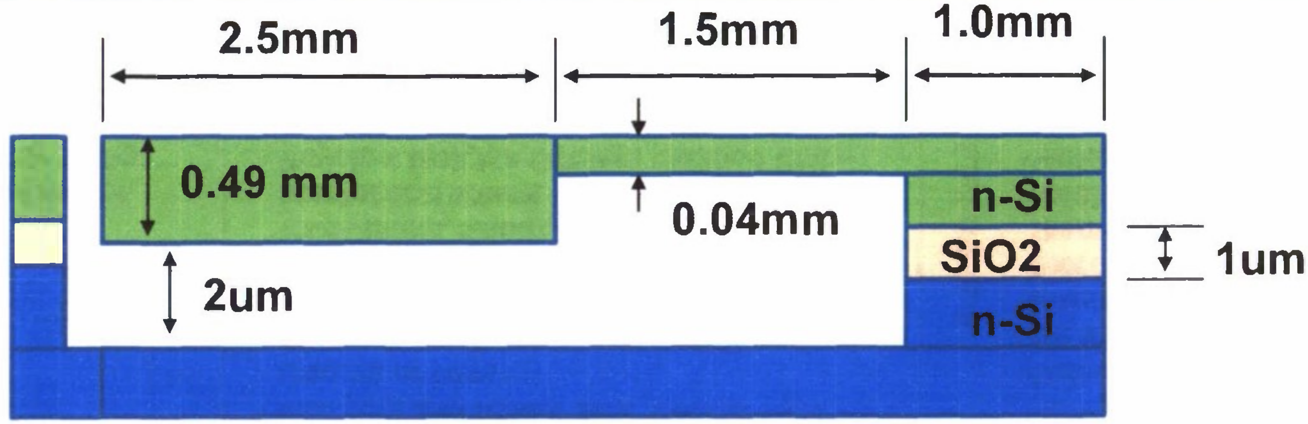
END-OF-PHASE GOALS

- Deliver compact model for MEMS resonators
- Include electro-mechanical, electro-thermal and thermo-mechanical effects
- Validate model with ±0.5dB accuracy
- Code in Verilog and demonstrate portability between ADS and CADENCE

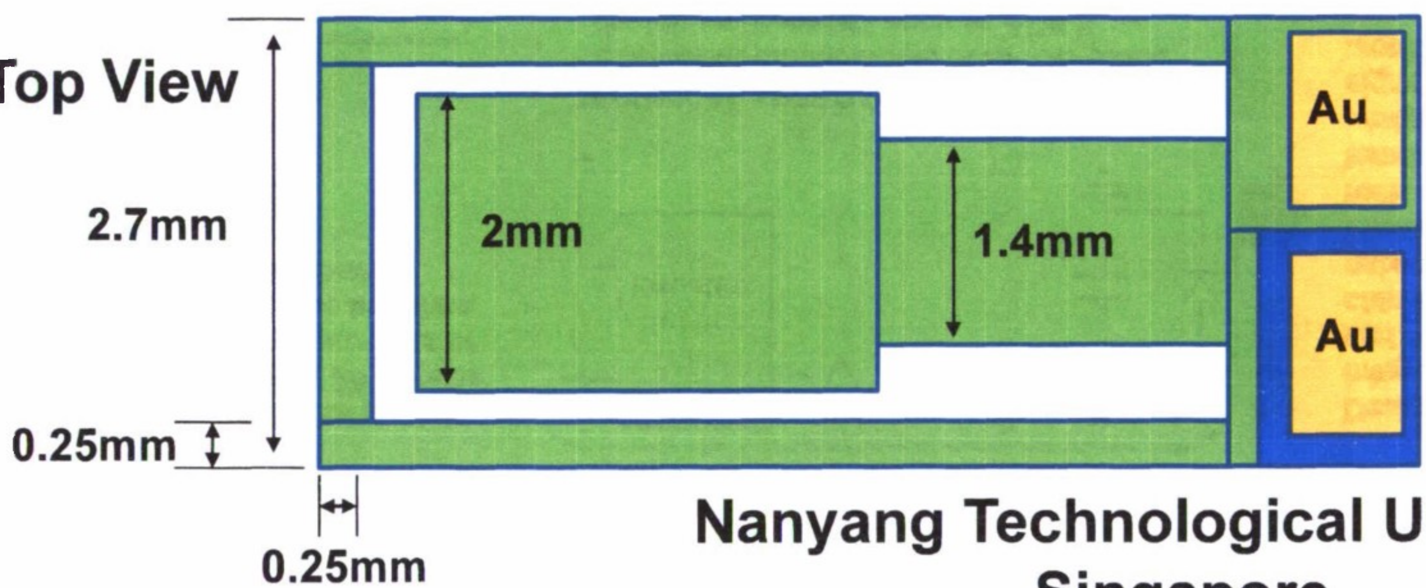
Design integrated mechanical circuits like electronic ICs

Resonator Formed by Wafer Bonding

Side View

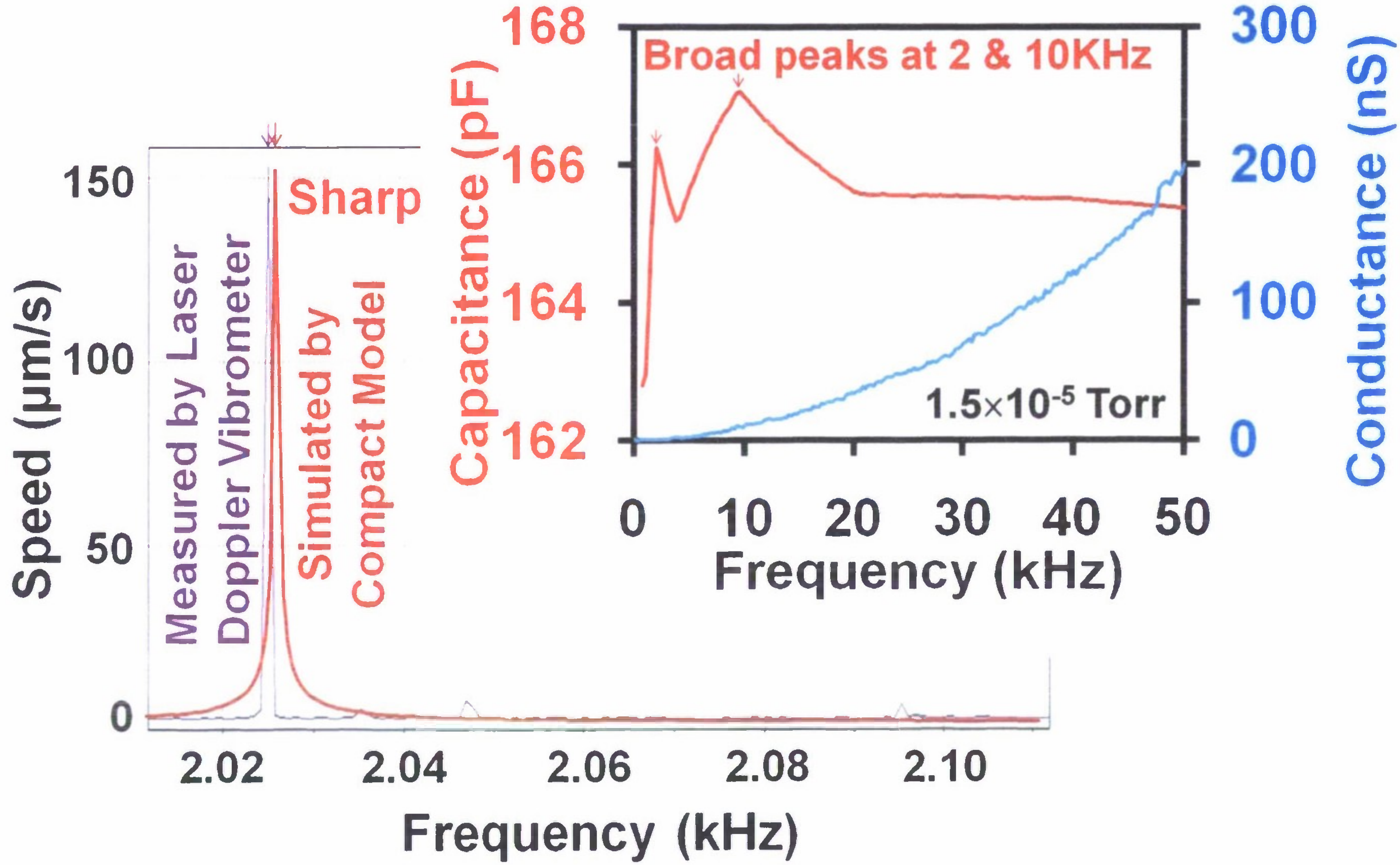


Top View

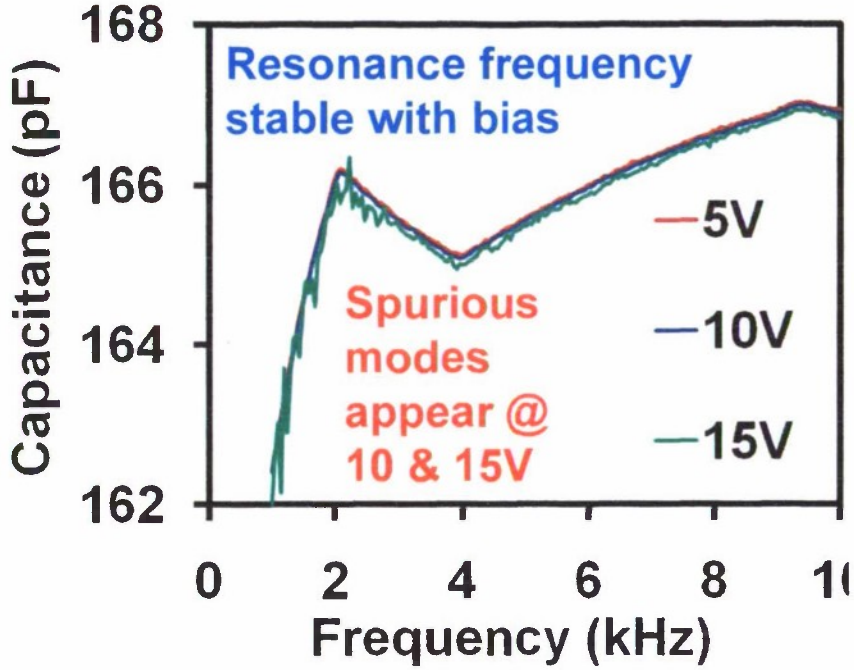


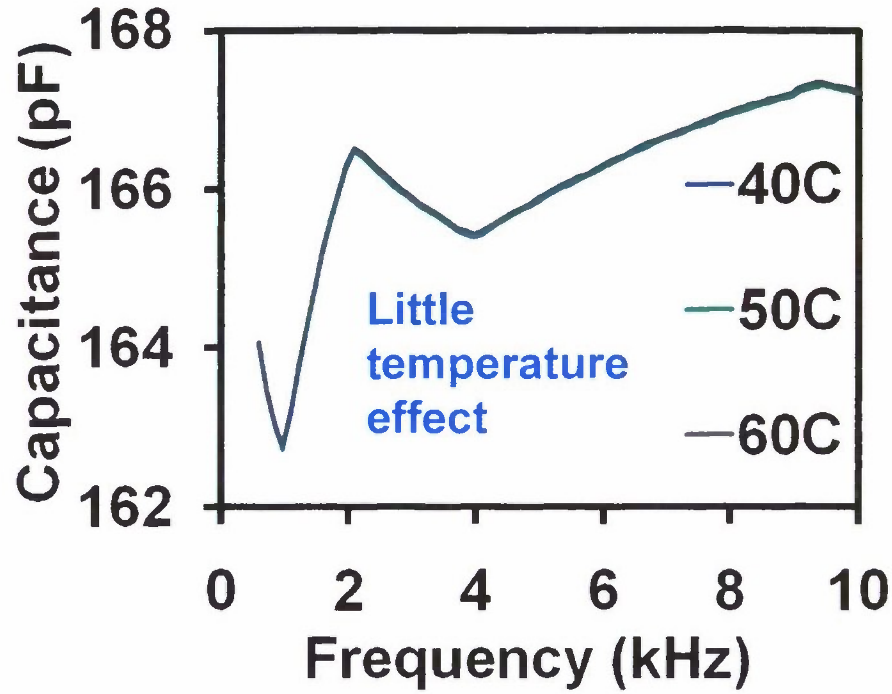
Nanyang Technological University
Singapore

Mechanical vs. Electrical Resonance

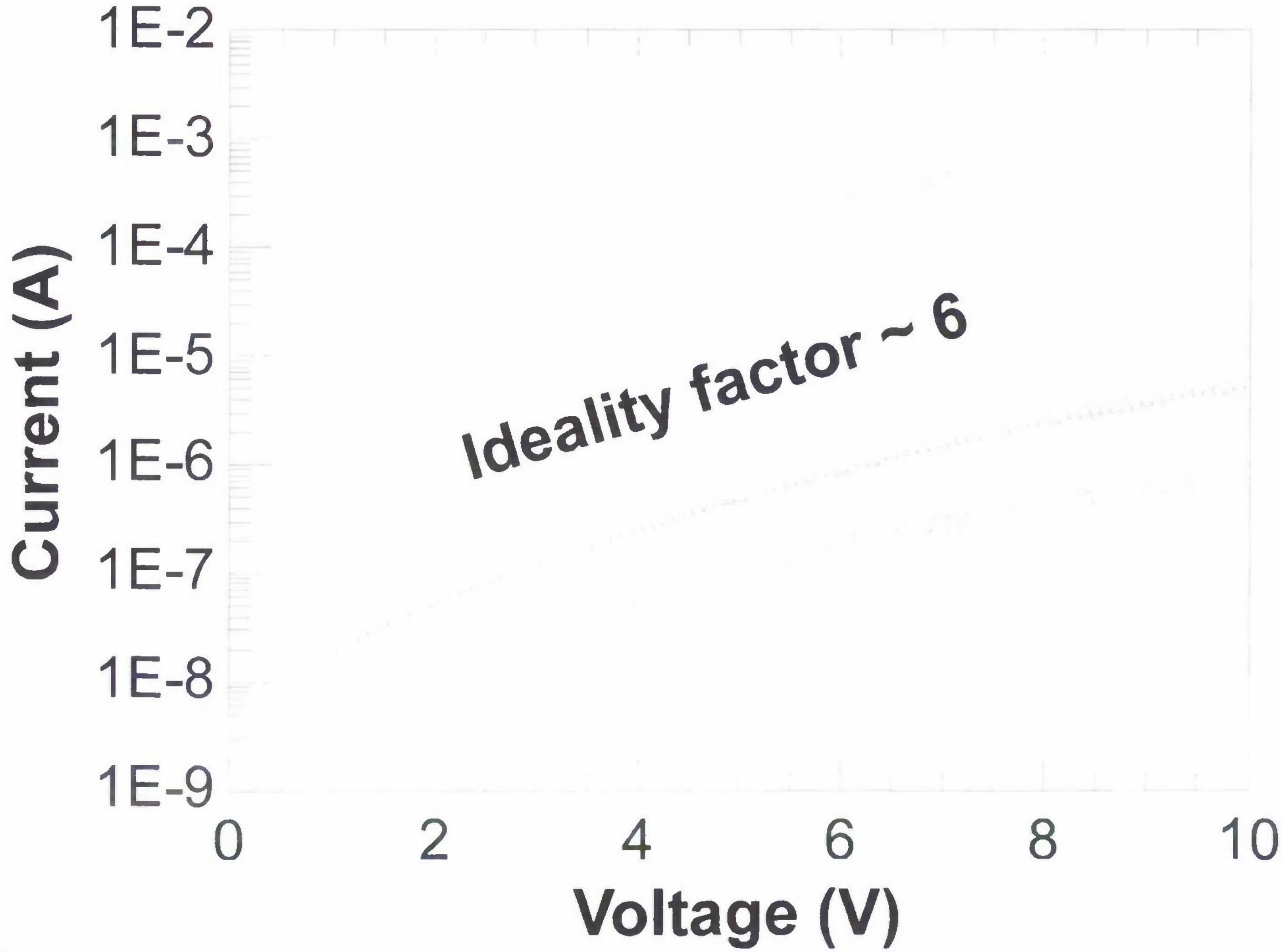


Bias & Temperature Effects





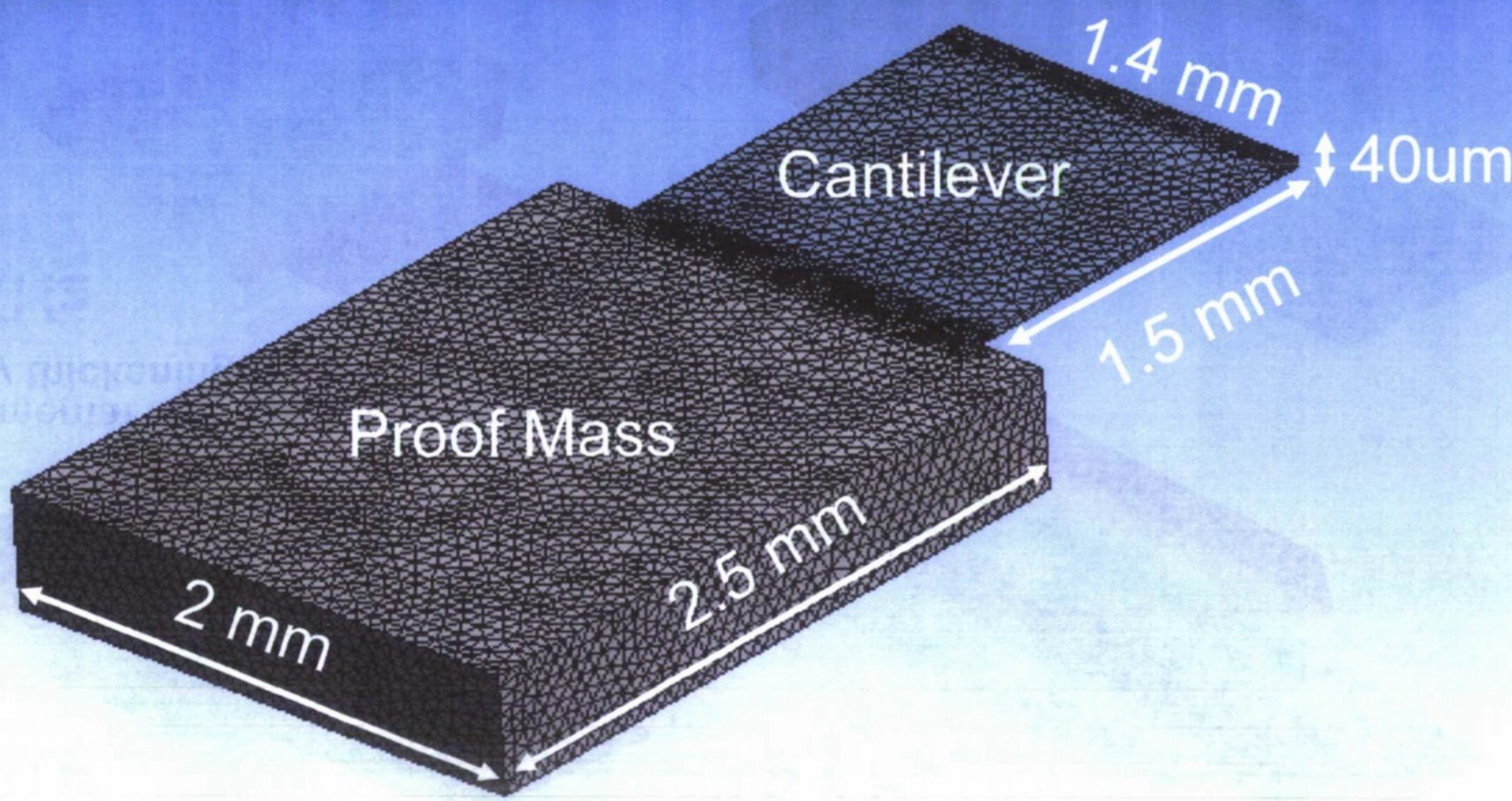
Leakage Broadens Electrical Resonance



Properties of Silicon

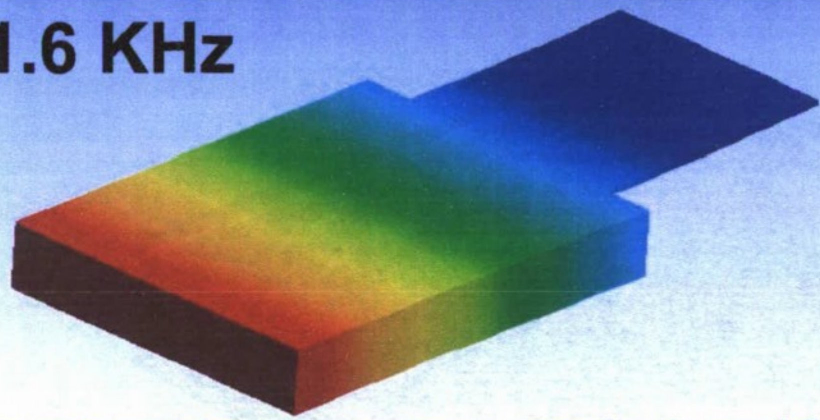
Density	2.33×10^{-15} kg/μm^3
Coeff. of Expansion	2.65×10^{-6} /°C
Thermal Conductivity	1.56×10^{8} pW/μm/°C
Specific Heat	7.13×10^{14} pJ/kg/°C
Resistivity	2×10^{10} mΩ μm
Young's Modulus	1.69×10^{5} MPa
Poisson's Ratio	6.4×10^{-2}
Bulk Modulus	6.46×10^{4} MPa
Shear Modulus	7.94×10^{4} MPa

Finite-Element Analysis by ANSYS

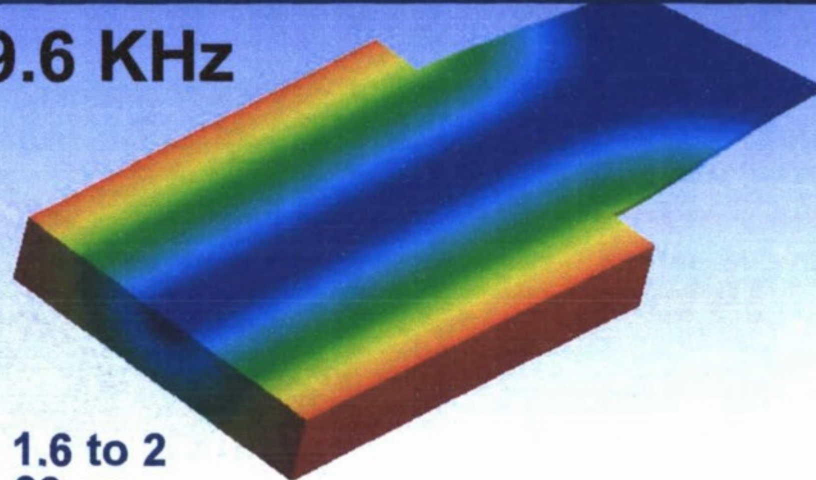


Simulated Resonance Modes

1.6 KHz

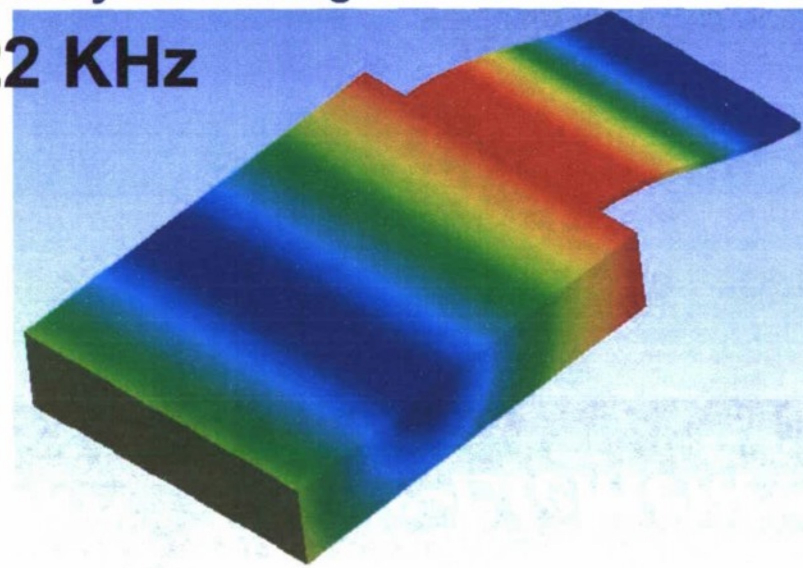


9.6 KHz

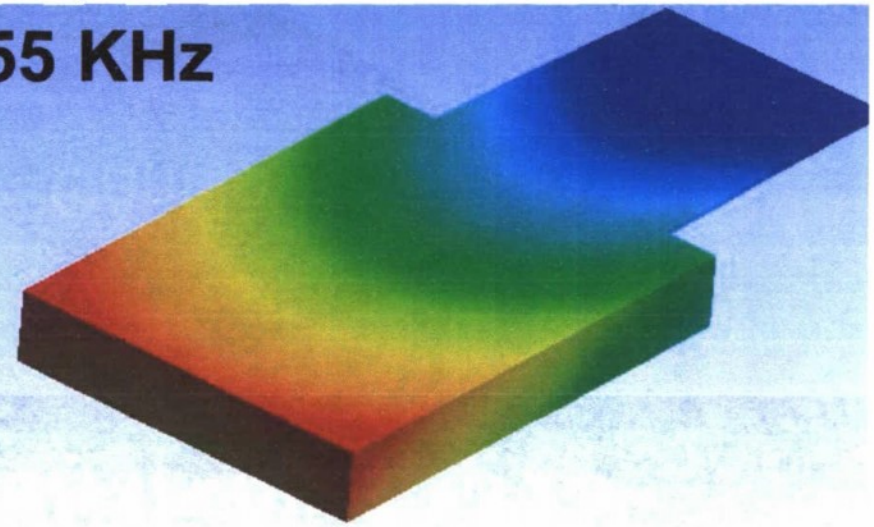


Fundamental resonance can be tuned from 1.6 to 2 KHz by thickening the cantilever from 40 to 60 µm

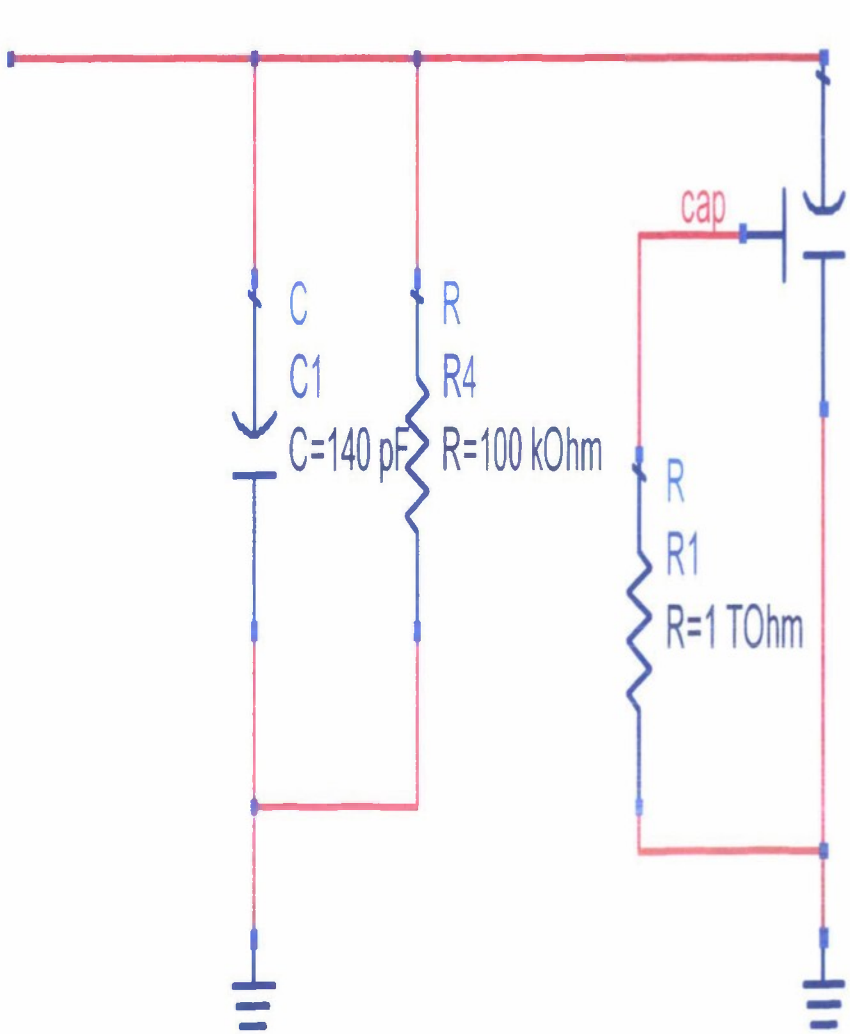
22 KHz

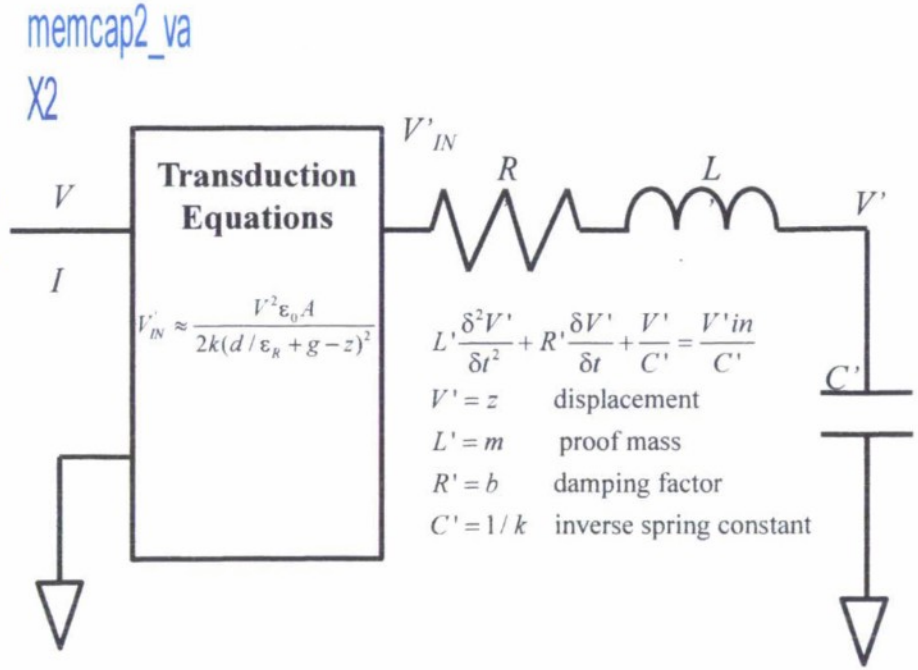


55 KHz



Compact Resonator Model

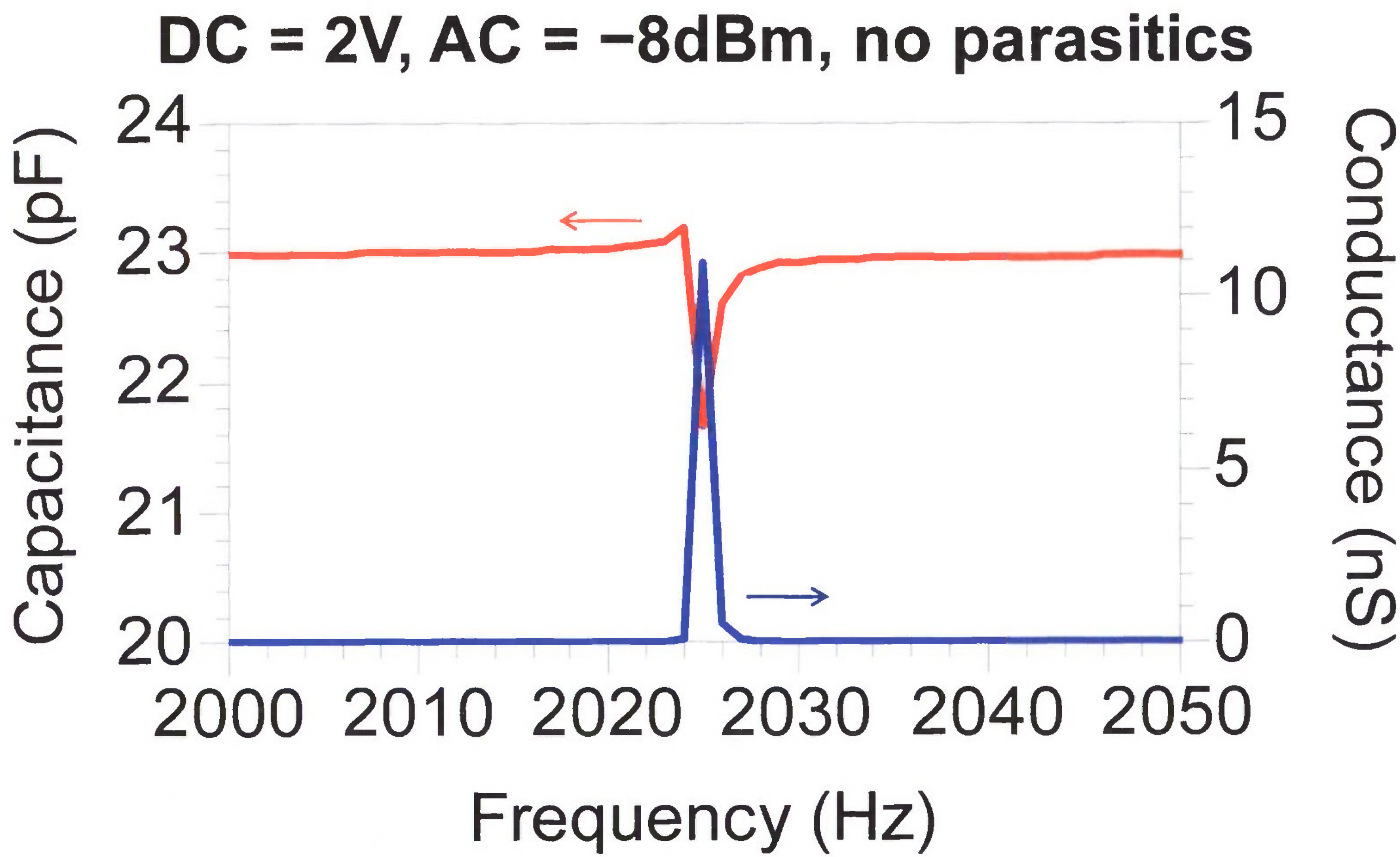




C1 and R4 are real parasitics

R1 is fictitious to ensure convergence during simulation

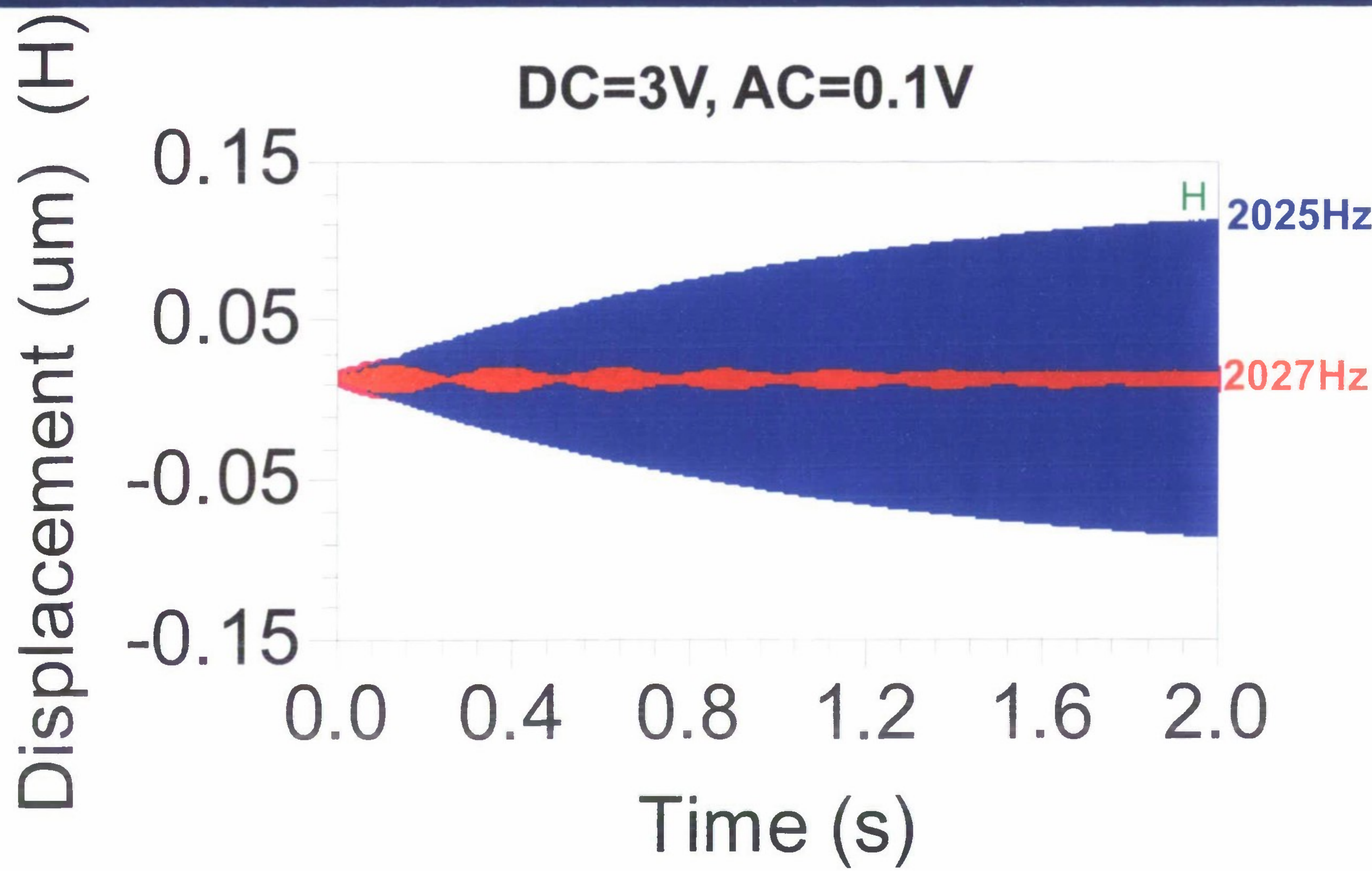
Resonance Simulation



m=5.7mg, k=3745N/m, b=10^{-5}N.s/m, A=5mm^2, g=2um

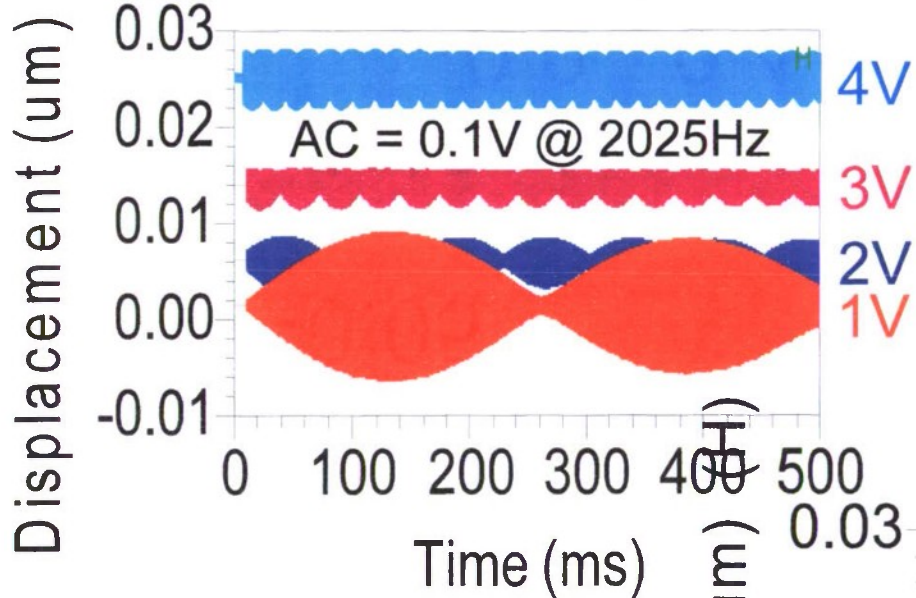
Transient Simulation

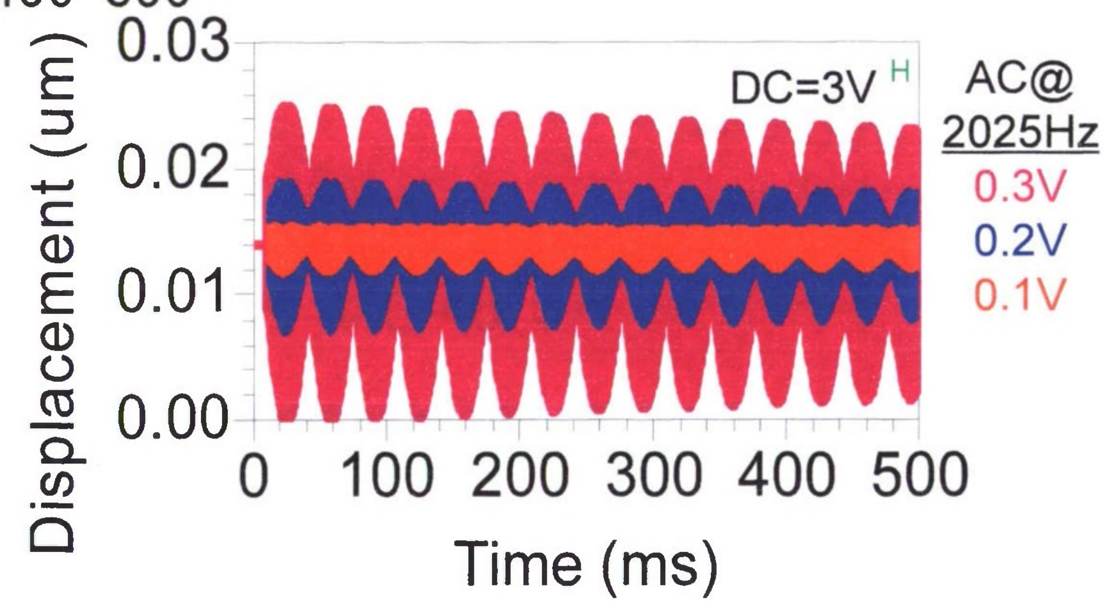
DC=3V, AC=0.1V



Resonance grows quickly @2025Hz, but diminishes @2027Hz

Effects of DC Bias & AC Drive





Conclusion

- Compact resonator model developed for small-signal/ large-signal and time-domain/frequency domain simulations
- Model validated only at small-signal steady-state conditions
- Further validation awaits better samples with less leakage and more thorough electrical and mechanical characterization